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OXIDATIVE TORREFACTION FOR PULVERIZED PALM BIOMASS USING AIR

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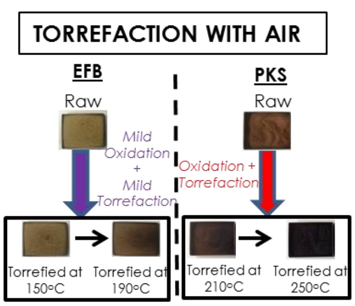
Graphical abstract



Abstract

Torrefaction is one of the promising ways to utilize abundant amount of empty fruit bunch (EFB) and palm kernel shell (PKS) while upgrading the combustion properties of both types of palm biomass. However, the supply of costly inert gas during torrefaction process such as nitrogen in large industrial sector may not be economical. Therefore, in the present study, air is used instead of nitrogen for the torrefaction process. The EFB and PKS were torrefied separately in a 60 mm diameter and 300 mm length of horizontal tubular reactor under various temperatures of 150°C to 190°C and 210°C to 250°C, respectively for 30 minutes using air. The torrefaction with nitrogen was also performed for comparison purpose. At the respective maximum temperature, energy yields of the torrefied EFB for the case of oxidative (air) torrefaction and nitrogen torrefaction are around 95% and 88%, respectively while energy yields of PKS for the case of oxidative(air) and nitrogen torrefaction are around 69% and 83%, respectively due to the weight loss after removal of volatile matter during torrefaction process. Besides that, the calorific values are enhanced after being torrefied with air (mere 4% for EFB and 18% for PKS when the respective maximum temperature was used).

Keywords: Empty fruit bunch, palm kernel shell, oxidative torrefaction, torrefaction, air torrefaction

1.0 INTRODUCTION

Emission of greenhouse gases adversely affects the environment that is caused by uncontrolled fossil fuel combustion and deforestation activities. One of the effective ways to cope up with the increasing energy demand scenario while reducing the risk of climate change is strong dependence on various renewable energy sources such as solar, wind, mini hydro and biomass [1]. In Malaysia, the main contributors in renewable energy shares are biomass and solar [2]. Palm biomass is being actively cultivated in Malaysia that covers close to five million hectares in year 2011 [3]. In year 2014, the area covered by palm oil plantation has been recorded to reach 5.39 million hectares [4]. Table 1 shows the energy values of various renewable energy sources that are available in Malaysia. The table elucidates how important the role of palm biomass in power generation sector. Biomass in general, has several drawbacks such as hygroscopic characteristic, high oxygen and moisture contents, poor grindability, low density values and lignocellulosic heterogeneity of material [5]. One of the best ways to upgrade properties of raw biomass is by applying combined technique of densification and followed by torrefaction or vice versa [6-10].

Table 1 Renewable and potential energy resources in Malaysia [11]

Renewable energy sources	Energy value (RM million per year)
Forest residues	11,984
Oil palm biomass	6,379
Solar thermal	3023
Mill residues	836
Hydro	506
Solar PV	378
Municipal waste	190
Rice husk	77
Landfill gas	4

Torrefaction enhances the combustion properties of biomass by removing moisture and volatile matters from the raw materials. This pretreatment is necessary to convert the raw biomass into biofuel with viable performance. The performance of the torrefied products are affected by several operating parameters such as type of biomass, torrefaction temperature, and residence time [12].

Recently, torrefaction using non-inert gases has been introduced in order to reduce the dependence on costly nitrogen [13, 14]. Number of researches have been conducted [5,13-20] to investigate the performance of torrefied biomass produced under various non-inert environments, and with the aim to utilize flue gas from charcoal combustion [14], biomass combustion [17,20], combustion in palm industries [13,18], and oxy-fuel combustion [19]. In the present study, torrefaction was performed for empty fruit bunch (EFB) and palm kernel shell (PKS), under various temperatures of 150℃ to 190℃ and 210℃ to 250℃, respectively. EFB and PKS are two major types of waste obtained from the processing of fresh fruit bunch (FFB) [21]. EFB was selected due to its abundance while PKS was selected due to its highest calorific value if compared with the other major biomass wastes (EFB and mesocarp fibre) [21]. Based on the literature review conducted, for the case of EFB and PKS, the torrefaction by using air has not been performed yet, thus this subject becomes as the main focus of this paper. In the present study, the physical characteristics such as mass loss and mass yield, and combustion properties such as gross calorific value, energy yield, moisture content, volatile matter, fixed carbon and ash content were determined and evaluated by comparison with benchmark ISO, EN and DIN standards.

2.0 METHODOLOGY

2.1 Preparation of Raw Materials

The shredded Empty fruit bunch (EFB) and palm kernel shell (PKS) were obtained from a palm oil mill. The shredded EFB and PKS were then ground into powder form. Then, both pulverized EFB and PKS were sieved by using sieved shaker. In the present study, the particles with the size of below than 500 µm were used. The characterization tests were carried out to determine the physical and combustion properties of the raw EFB and raw PKS.

2.2 Torrefaction Experiment

Figure 1 demonstrates the schematic diagram of setup for torrefaction experiment. The setup consists of stainless steel tubular reactor covered with plate heater, flow meter, PID temperature controller, thermocouples, pressure regulator and tanks for compressed air and nitrogen. The length and diameter of the torrefaction reactor are 300 mm and 60mm, respectively. Two K-type thermocouples were located at the outlet and the middle of the reactor. The tip of each thermocouple was set in such a way that vertical distance between the tip and the sample was around 1 mm. Approximately 10 g of sample was put evenly into an aluminum tray with dimension of 56 mm x 45mm x 13 mm and then was put inside the inner tubular reactor. During the experiment, three trays with same size were used for each operating condition. The experiment consists of two part; the first part is torrefaction with air as working gas and the second part is torrefaction with nitrogen as working gas. The pulverized EFB and PKS were heated separately under various torrefaction temperatures of 150℃ to 190℃ and 210℃ to 250℃, respectively for residence time of 30 minutes. For the case of EFB, when torrefaction with air was performed at temperature of 200℃ or above, the temperature reading became very unstable, that is supposed due to the very reactive oxidation reaction [13]. This situation causes burnout of portion of EFB. Therefore, relatively low temperature was applied for the torrefaction of EFB. Throughout the experiment, constant volume flow rate of 1 l/min of air or nitrogen was used during the torrefaction. The volatile compounds and non-condensable matter produced from decomposition of biomass were channelled to a safe exhaust ventilation system.

After being torrefied for 30 minutes at the desired temperature, the heater was turned off and the torrefied biomass was cooled down to temperature of below than 40℃. The torrefied biomass was then removed from the reactor.

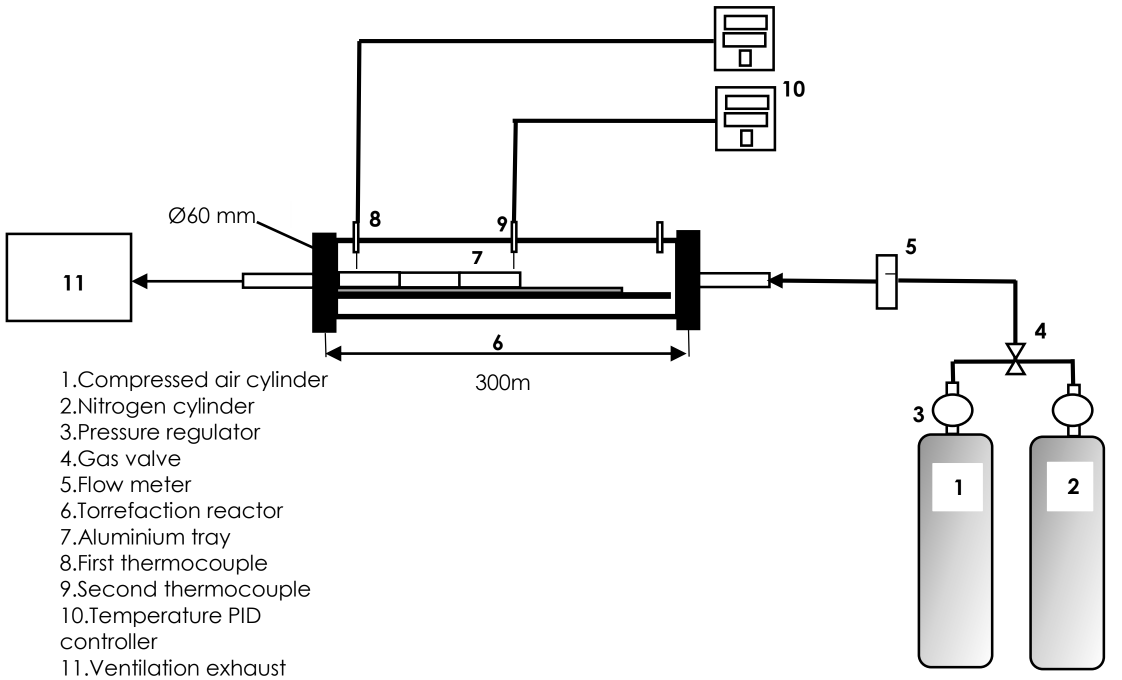


Figure 1 Schematic diagram of setup for torrefaction experiment

2.3 Determination of Mass Yield and Energy Yield

During torrefaction process, mass loss occurs due to dehydration and partial devolatization [22]. Therefore, it is important to determine mass yield of the torrefied samples. Energy yield is also an important property to understand how much energy of the raw biomass is preserved after experiencing torrefaction treatment. All samples (before and after torrefaction) were weighed by using a mechanical precision balance (model FX-300i, standards applicable: EN61326) to determine mass yield by following method applied by Uemura *et al*. [24]. Meanwhile, to measure gross calorific value for calculation of energy yield, the standard method of ASTM D240 was applied by using IKA calorimeter system (model C2000). The equations for mass yield and energy yield are shown as follows [23, 24],

Mass Yield = (Mass after torrefaction)/(Mass before torrefaction) x 100 (1)

Energy Yield=Mass Yield x Calorific Value Ratio (2)

where

Calorific Value Ratio= (Calorific value after torrefaction)/(Calorific value of raw material) (3)

2.4 Determination of Gross Calorific Value

The standard method used for gross calorific value determination is ASTM D240. The test was performed by using IKA calorimeter system (model C2000) that is located at Combustion Laboratory of Faculty of Mechanical Engineering, UTM Johor Bahru. In the present study, gross calorific values were determined for torrefied samples as well as raw materials.

2.5 Ultimate and Proximate Analysis

Ultimate analysis was performed by using CHNS analyzer (model: vario MICRO CUBE) to determine the elements of raw palm biomass. Meanwhile, proximate analysis was performed to determine the moisture, volatile matter, ash and fixed carbon content of the raw materials and torrefied biomass samples. The standards used for determination of moisture, volatile matter and ash content are ASTM D3173, ASTM D3175 and ASTM D3174, respectively.

3.0 RESULTS AND DISCUSSION

3.1 Characterization of Raw Materials

The average gross calorific values of the raw EFB and PKS were found to be 16812.5 kJ/kg and 17827 kJ/kg, respectively. Based on the results obtained, it can be said that the gross calorific value of the raw EFB is lower than the benchmark for commercial purpose, that is DIN51731 (>17500 kJ/kg). Meanwhile, the gross calorific value of the raw PKS is slightly higher than the benchmark. Overall, it can be said that the values obtained in the present study are comparable with that obtained by the previous studies [13, 24].

Table 2 shows the results of ultimate analysis for both raw materials. It was found that the results were very close with the results obtained by other researchers [24], in which carbon composition is the highest (around 45%). Meanwhile, Table 3 shows the results of proximate analysis. Based on Table 3, it can be said that the content of volatile matter is significantly high for both raw EFB and PKS, thus implies the importance of the torrefaction to upgrade the biomass properties by removing the volatile matter. Based on EN 14774-3 standard, the permissible limit of moisture content for commercialization of torrefied product is 10%, thus implies the potential of both EFB and PKS used in the present study to be torrefied without any drying pretreatment. In terms of ash content, both raw materials have sufficiently low value, that is around 3%. If referring to ISO 18122 standard, the acceptable range of ash content for commercialization of torrefied solid fuel is the value must be equal or less than 5%. Based on the previous studies [20, 25], the ash content of the raw biomass supposed to increase after torrefaction treatment.

Table 2 Ultimate Analysis for Raw Materials of Empty Fruit Bunch and Palm Kernel Shell

	EFB	PKS
Carbon (%)	44.20	45.19
Hydrogen (%)	5.82	5.95
Nitrogen (%)	0.64	0.33
Sulphur (%)	0.095	0.038

Table 3 Proximate Analysis for Raw Materials of Empty Fruit Bunch and Palm Kernel Shell

	EFB	PKS
Moisture (%)	9.15	9.30
Volatile Matter (%)	82.35	75.91
Fixed Carbon (%)	5.46	11.76
Ash (%)	3.04	3.03

3.2 Mass Yield

Figures 2 and 3 show the results of mass yield for torrefied empty fruit bunch (EFB) and torrefied palm kernel shell (PKS), respectively. Here, it is important to note that torrefaction temperature range for the case of EFB is 150℃ to 190℃ while for the case of PKS is higher, that is 210℃ to 250℃. Based on the previous study that performed nitrogen torrefaction within the temperature range of 220℃ to 300℃ [24], it was found that the mass yield of torrefied EFB is significantly lower if compared to that of PKS. Thus, this reveals that the contradictable result obtained in the present study is mainly due to the different operating temperature applied for EFB and PKS.

Figure 2 demonstrates that when the temperature is increased from 150℃ to 190℃, the mass yield of torrefied EFB for the case of air torrefaction decreases slightly from 94.6 % to 91.4% while for the case of torrefaction with nitrogen, almost no change was observed, and the mass yield values were around 92 %. Based on the trends obtained in the present study and thermogravimetric (TGA) analysis performed by Nyakuma *et al*. [22], the slight decrease in mass yield of EFB within this temperature range (150℃ to 190℃) for the case of oxidative (air) torrefaction is mainly due to the oxidation process instead of devolatilization process.

However, mass yield of PKS decreases significantly due to torrefaction, whether by using air or nitrogen. When the torrefaction temperature is increased from 210℃ to 250℃, the mass yield of PKS for the case of oxidative (air) torrefaction and nitrogen torrefaction decreases, from 80% to 58.9% and 86.5% to 71.1%, respectively. Within this temperature range, the decrease in mass yield for the case of nitrogen torrefaction is mainly due to the mass loss caused by the dehydration and partial devolatilization processes while for the case of oxidative (air) torrefaction, additional process occurs, that is oxidation process of unstable components [13]. The occurrence of oxidation process causes the mass loss of PKS becomes more significant. Furthermore, when the temperature is increased, the role of partial devolatization and oxidation processes in reducing the mass yield of PKS becomes more significant, thus the mass yield decreases.

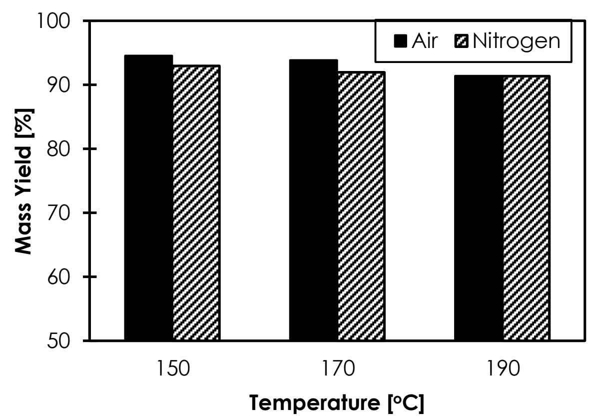


Figure 2 Mass yield of torrefied EFB for the cases of oxidative (air) and non-oxidative (nitrogen) torrefaction

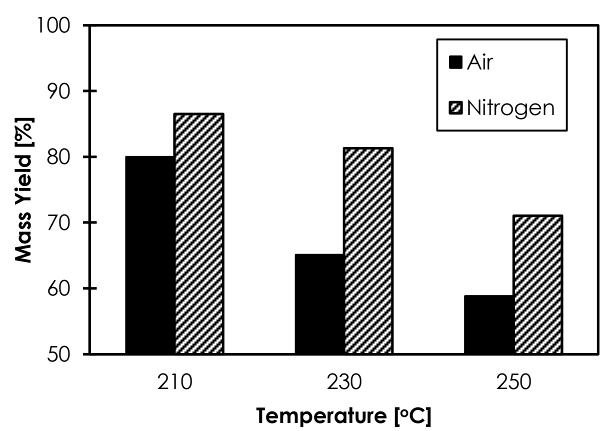


Figure 3 Mass yield of torrefied PKS for the cases of oxidative (air) and non-oxidative ((nitrogen) torrefaction

3.3 Gross Calorific Value

Figures 4 and 5 show the results of gross calorific value for torrefied EFB and torrefied PKS. The data for raw EFB and raw PKS are also enclosed for comparison purpose. Figure 4 demonstrates that the calorific value of the EFB is slightly enhanced after oxidative (air) torrefaction at 190℃, from 16.81 MJ/kg to 17.48 MJ/kg. Based on the results, it can be said that only the case of oxidative torrefaction under temperature of 190℃ gives the calorific value that is very close to the benchmark for commercialization, as stated by DIN51731 (>17500 kJ/kg). This is primarily due to the increase in fixed carbon content. However, in the present study, an increase in temperature does not necessarily enhance the calorific value of EFB for both types of torrefaction. Therefore, it can be concluded that the torrefaction temperature of 150°C to 190°C is not really practical for both types of torrefaction.

Meanwhile, Figure 5 shows that when the torrefaction temperature is increased from 210℃ to 250℃, the improvement of gross calorific value of PKS also increases from around 8% to 18%, regardless of type of torrefaction. Based on the findings obtained by Wang *et al*. [16], the improvement in gross calorific value if compared to untreated raw PKS is mainly due to an increase in carbon element and a decrease in hydrogen and oxygen content. It is interesting to note that at the same temperature, the gross calorific values of torrefied PKS for the case of oxidative (air) torrefaction and nitrogen torrefaction are close to each other, even though the values of mass yield are significantly different. This condition proves that the use of air during oxidative torrefaction does not affect the gross calorific value. The similar trend has been obtained by Uemura *et al*. [13] who performed oxidative torrefaction (with maximum oxygen concentration of 15%) on EFB at temperature of 220℃ to 300℃. The insensitivity of gross calorific values to the type of torrefaction (non-oxidative and oxidative) was also discovered by Chen *et al*. [5] who performed torrefaction on palm oil fiber pellets for various oxygen concentration (0-10 vol%). Overall, it was found that all gross calorific values of PKS meet the requirement for commercialization, as stated by DIN 51731 (>17500 kJ/kg).

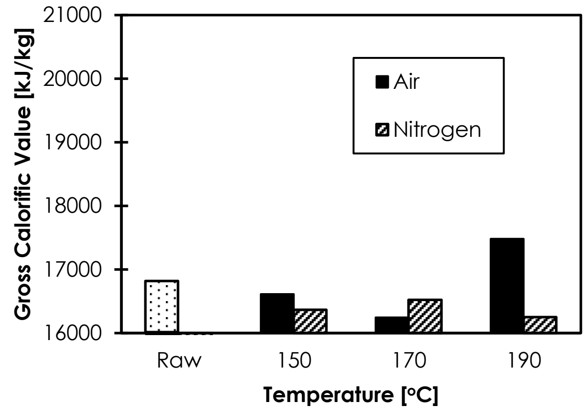


Figure 4 Gross calorific value of raw and torrefied EFB (for the cases of oxidative(air) and non-oxidative (nitrogen) torrefaction)

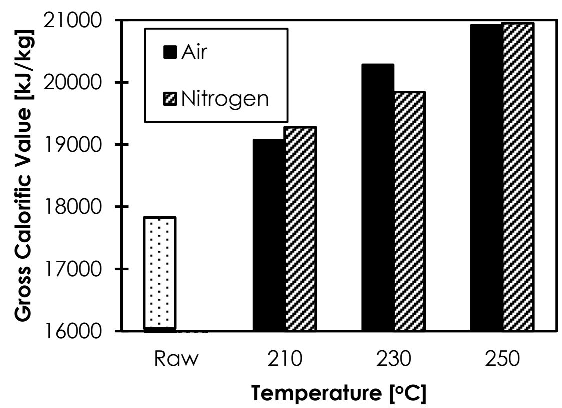


Figure 5 Gross calorific value of raw and torrefied PKS (for the cases of oxidative (air) and non-oxidative (nitrogen) torrefaction)

3.4 Energy Yield

Figures 6 and 7 demonstrate energy yield for torrefied EFB and torrefied PKS, respectively. Here, Eq. (2) is used to obtain energy yield. Based on Figure 6, it can be said that all values of energy yield for torrefied EFB are above 88%, thus implies that most of energy that contained in raw EFB are preserved. Sufficiently high energy yields were obtained because the torrefaction treatment applied for EFB in the present study was very mild. However, the performance of the torrefied EFB is still unsatisfactory because improvement of gross calorific value could not be clearly observed, as demonstrated by Figure 4 in Section 3.3.

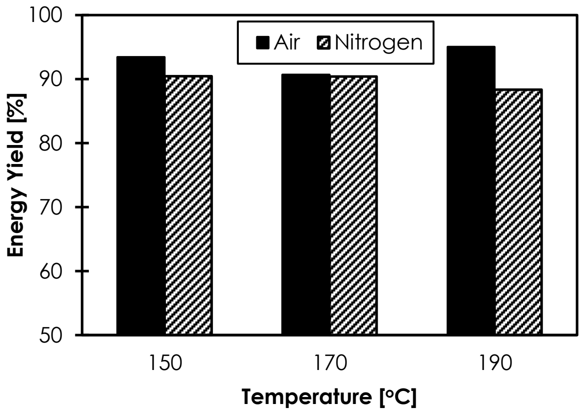


Figure 6 Energy yield of torrefied EFB for the cases of oxidative (air) torrefaction and non-oxidative (nitrogen) torrefaction

Meanwhile, Figure 7 demonstrates that the energy yields of torrefied PKS for the case of oxidative (air) torrefaction are lower than that for the case of nitrogen torrefaction. This is because lower mass yields were obtained from oxidative (air) torrefaction. When torrefaction temperature is increased from 210℃ to 250℃, the energy yield of torrefied PKS for the case of oxidative (air) torrefaction drops from 86% to 69%, whereas for the case of nitrogen torrefaction, the energy yield drops from 94% to 83% only. It was found that the energy yields obtained from nitrogen torrefaction in the present study were close to the energy yields obtained by Uemura *et al*. [24]. Based on the overall result of energy yield, it was found that the trend of energy yield with respect to torrefaction temperature is significantly affected by mass yield rather than calorific value ratio.

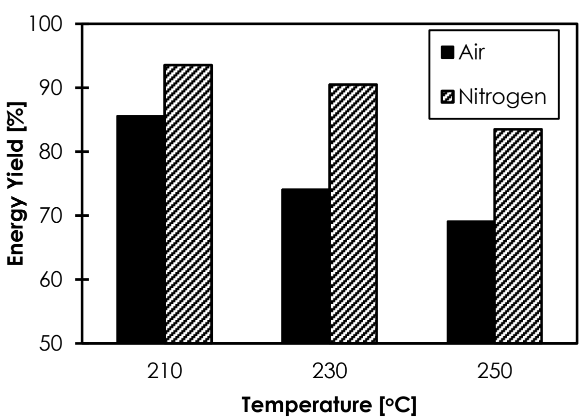


Figure 7 Energy yield of torrefied PKS for the cases of oxidative (air) torrefaction and non-oxidative(nitrogen) torrefaction

3.5 Proximate Analysis

The results of proximate analysis for torrefied EFB and torrefied PKS are shown in Figure 8. Based on Figure 8 and Table 3, it can be clearly seen that when the pulverized EFB is torrefied using air at temperature of 190℃, fixed carbon content increases from 5.5% to 9.9%, whereas the volatile matter is reduced from 82.4% to 77.5%. The increase in fixed carbon content reveals the occurrence of slight partial devolatization even during the mild torrefaction. Based on Figure 8, it can be said that the torrefaction using air (oxidative torrefaction) gives higher fixed carbon content and lower volatile matter if compared to the case of torrefaction using nitrogen (non-oxidative torrefaction) at the same operating temperature. This can be elucidated by the higher reaction rate when using air for torrefaction, thus resulting in higher fixed carbon content and lower volatile matter. In terms of moisture content, all values are within the range of 9% to 11%, thus very close with the requirement stated by benchmark EN 14774-3 standard (<10%) and very competitive if compared with solid fuel that contains commonly used mixture of mesocarp fibre and palm kernel shell with weight ratio of 60:40 (moisture content of 12.5%) [26]. In terms of ash content, all values fulfill the requirement stated by ISO 18122 standards (≤5%) and also lower than the ash content of solid fuel that contains commonly used mixture of mesocarp fibre and palm kernel shell (ash content of 5.8%) [26].

Meanwhile, as shown by Figure 8, the changes in volatile matter and fixed carbon contents for the case of torrefied PKS can be clearly observed when temperature is increased from 210℃ to 250℃. When the torrefaction was performed by using air, volatile matter decreases from 74.6% to 60.5% and fixed carbon content increases from 14.0% to 25.5%, whereas when the torrefaction was performed by using nitrogen, volatile matter decreases from 75.6% to mere 68.8% while fixed carbon content increases from 14.0% to mere 20.8% only. Within this temperature range, the partial devolatization process plays a significant role in affecting the trend of changes in volatile matter and fixed carbon content for both types of torrefaction [22]. However, for the case of oxidative (air) torrefaction, oxidation process also occurs in parallel to partial devolatization process [13]. Based on the results, all values of moisture content of torrefied PKS are found to fulfill the requirement as stated by EN 14774-3 standard (<10%), and all values of ash content also are found to fulfill the requirement as stated by ISO 18122 standard (≤5%), and are very competitive if compared to the ash content of solid fuel that contains commonly used mixture of mesocarp fibre and palm kernel shell (5.8%) [26].

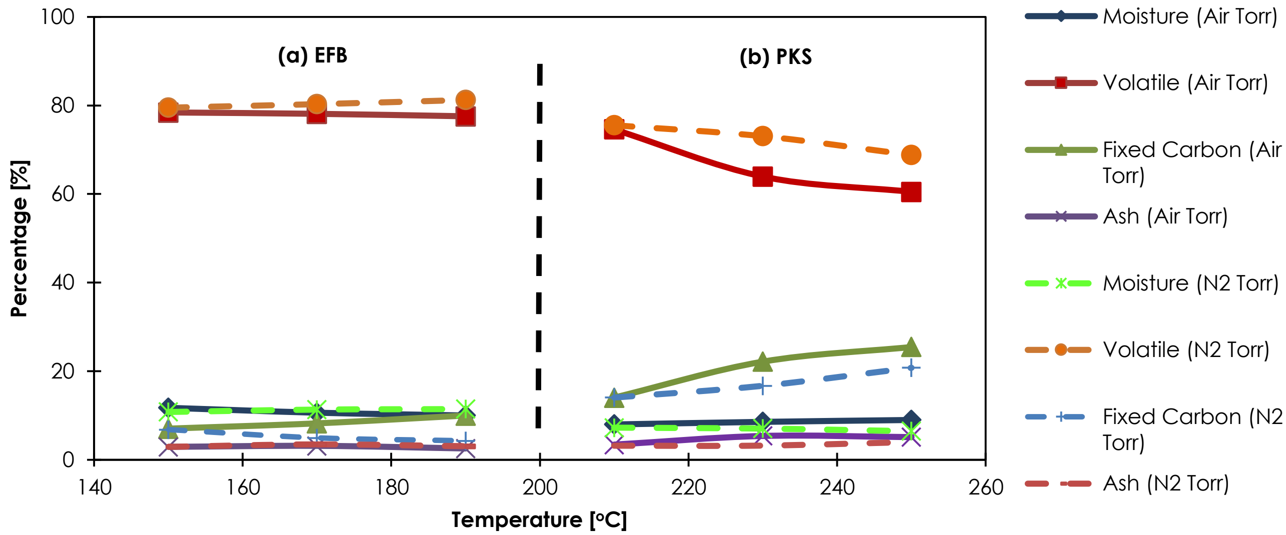


Figure 8 Proximate analysis for (a) torrefied EFB and (b) torrefied PKS

4.0 CONCLUSIONS

In the present study, oxidative torrefaction has been performed by using air on pulverized empty fruit bunch (EFB) and pulverized palm kernel shell (PKS) for various temperatures of 150℃ to 190℃ and 210℃ to 250℃, respectively. Meanwhile, non-oxidative torrefaction was also performed by using nitrogen for comparison purpose.

For the case of oxidative torrefaction, both oxidation and devolatilization processes play an important role in modifying the physical structure and changing the properties of PKS. However, the oxidative torrefaction applied for EFB was very mild due to relatively low heating temperature, thus only slight changes in properties could be observed. For the torrefaction of PKS, torrefaction temperature significantly affects mass yield, energy yield and the results of proximate analysis. Even though energy yield for torrefied EFB is higher if compared to that for torrefied PKS, the performance of the torrefied EFB is still unsatisfactory because an improvement in gross calorific value could not be clearly observed.

Regardless of type of torrefaction, it was found that the gross calorific values, moisture and ash contents of torrefied PKS fulfil the requirements for commercialization, as stated by ISO, EN and DIN standards. Furthermore, these values are very competitive if compared to the performance of solid fuel that contains commonly used mixture of mesocarp fibre and PKS.

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